Proposal of flux retrieval methodologies for the BBR L2 baseline algorithms in the EarthCARE framework

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15 September 2010

Earth Radiation Budget Workshop

École Normale Supérieure (ENS)

Paris, France

ESA's Living Planet Programme

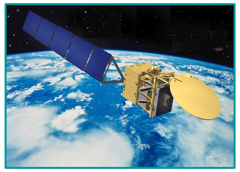
User driven missions

Earth Explorer
Research oriented

Core Missions

GOCE 2008

ADM-Aeolus 2011

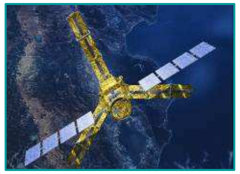


EarthCARE 2014

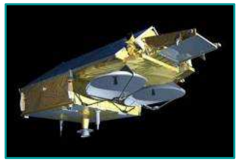
3 candidates:
BIOMASS
Core-H2O
PREMIER

Earth Explorer 7 2015

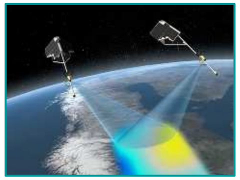
Opportunity Missions



SMOS 2009



CryoSat 2 2010



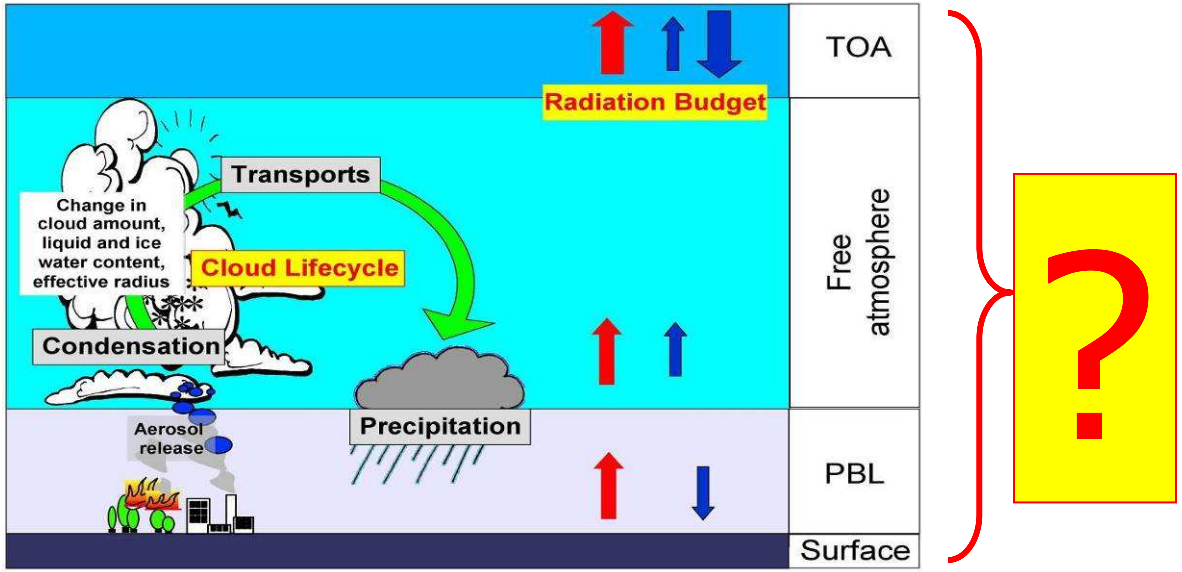
Swarm 2011

Earth Watch
Operational service

coop. with EUMETSAT
- **Meteosat**
- **MSG**
- **MTG**
- **EPS**
- **Post-EPS**

GMES
- **Sentinel 1**
  - *SAR imaging*
- **Sentinel 2**
  - *Superespectral high res. land imaging*
- **Sentinel 3**
  - *Ocean monitoring, mid-/low res. imagery + SAR*
- **Sentinel 4** **(on MTG)**
  - *Atmospheric chemistry*
- **Sentinel 5** **(on Post-EPS)**
  - *Atmospheric chemistry*
- **Sentinel 5-Precursor**
  - *Atmospheric chemistry*

SCOPE: Reduce current uncertainties related to aerosols and cloud interaction with radiation and climate to provide more secure foundation for predictions of future climate change



- Uncertainties in radiative forcing
  Indirect aerosol effects
- Uncertainties in climate response
  Cloud radiative feedbacks (climate sensitivity to radiative forcing)

Observation Technique – Mission Concept

Needs	Techniques	EarthCARE instruments
Aerosols: Vertical profiles of extinction and characteristics of aerosols	High spectral resolution lidar	ATLID HSRL
Clouds: Vertical profiles of liquid, super-cooled and ice water, cloud overlap, particle size and extinction	High spectral resolution lidar; Radar	ATLID HSRL; CPR Doppler
Vertical motion: Convective updraft and ice fall speed	Doppler Radar	CPR Doppler
2D context: Horiz. structure of clouds and aerosols	Multi-spectral Imager	MSI
Radiation and flux: SW and LW at Top of Atmosphere	Broad-band Radiometer	BBR

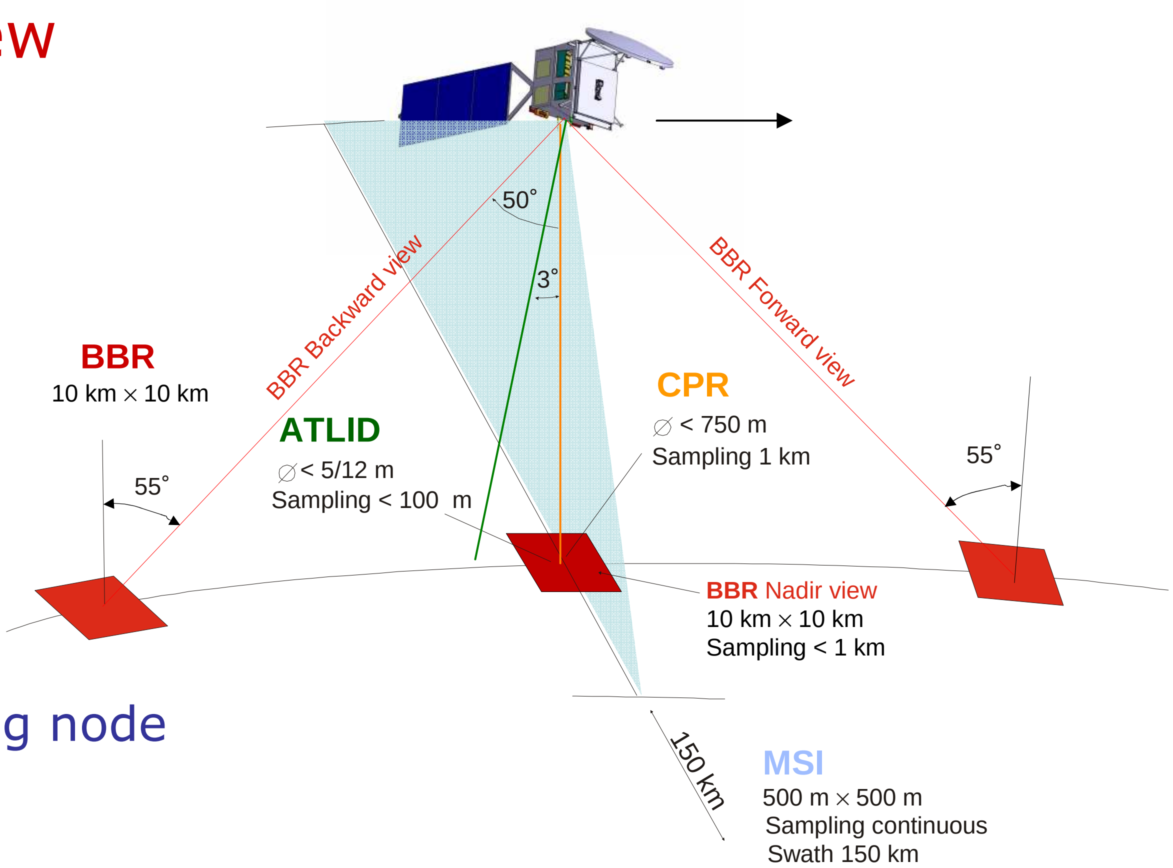
EarthCARE overview

Payload

- HSR Lidar at 355nm
- W-Band Doppler Radar
- Multi-spectral imager
- Broad-band radiometer

Satellite

- Polar sun-sync. orbit
- 13:45-14:00 descending node
- 410km mean altitude
- Launch: 2014

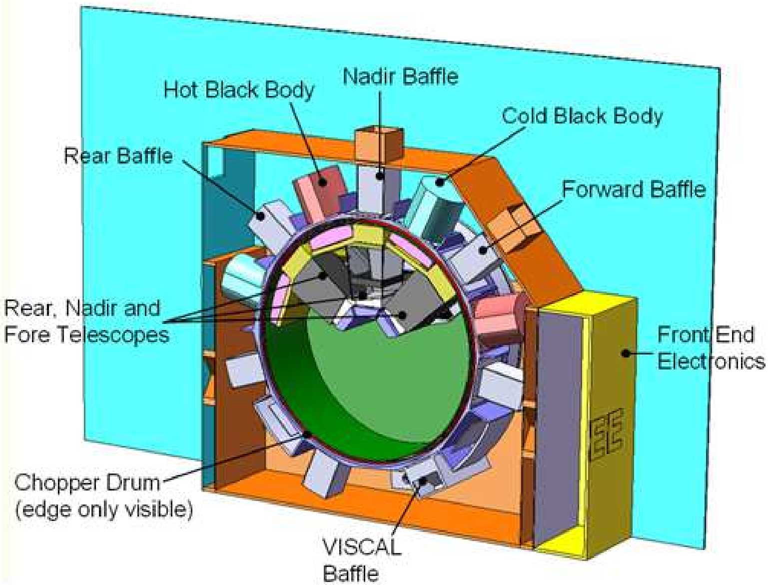


Stringent requirements for co-registration between instruments!

Industrial prime contractor: **Astrium GmbH**

Passive Instruments: Broad-band radiometer (BBR)

- Shortwave (0.2–4µm) and total wave channel (0.2–50µm)
- 3 along-track views: nadir, forward (+50/55°) and backward (-50/55°)
- Linear microbolometer array detectors, ground pixels < 1km x 1km
- Rotating chopper wheel (261 rpm)
- Calibration views: sun, internal cold and warm blackbodies
- 10km x 10km pixels spatially integrated in ground processing
- Radiometric accuracy: 2.5 W/m2.sr (SW), 1.5 W/m2.sr (LW)
- Horizontal along-track sampling: < 1km
- *Level 1 product: Filtered SW and LW TOA radiances*



Built by SEA with RAL as sub-contractor

BBR Optics Unit

GEOPHYSICAL (LEVEL 2) PRODUCTS Overview

CPR
Dopplerized Radar
- target mask
- ice & liquids clouds
- vertical motion
- precipitation

ATLID
High spectr. res. Lidar
- target mask
- extinction/backscatter
- aerosol
- ice clouds

MSI
Vis/NIR/SWIR/TIR
- cloud
- aerosol

BBR
Broad-band radiances
- shortwave
- longwave

Scene ID

flux retrieval algorithm

Synergistic products
- target classification
- ice cloud
- liquid cloud

Synergistic products
- aerosol

TOA flux estimates

compare

Reconstructed 3D-scenes of clouds and aerosols

RT modelled broad-band fluxes and heating rates

Flux retrieved from BBR measurements will be used to constrain the derivations of vertical profiles of Earth radiation budget components within the atmosphere

Baseline Radiance-to-Flux conversion: Approach

- Development of a BBR specific-designed ADM

  Two different approaches to define the flux retrieval procedure:

  – **Empirical development** (accumulated satellite data)

  BBR angular sampling (AT geometry) not appropriate to compute flux

  – **Theoretical development** (radiative transfer calculations)

  Exploit BBR multi-angular pointing capability, MSI multi-spectral info and synergy between active and passive sensors

- Use existing CERES ADM methodologies

  – **CERES TRMM ADM** (CERES PFM & VIRS)

  Angular models constructed with radiance measurements from tropical regions

  – **CERES Terra ADM** (CERES FM1-FM2 & MODIS)

  Consistency due to long series of accumulated multi-angular data

Shortwave BBR flux estimation: work plan

Scope: Retrieve instantaneous TOA shortwave radiative fluxes from the multi-directional broad-band and multi-spectral radiance measurements performed on-board the EarthCARE satellite

Goal: Develop radiance-to-flux conversion algorithms using synthetic ANN-based angular distribution models

Methodology: (i) Definition of the training sets obtained from the Terra CERES data base of TOA broad-band radiances and derived fluxes. (ii) Neural network training. (iii) Application of the network to data of interest for validation purposes

Study follows the operational procedure used in CERES SW ANN-derived ADM methodology *(Loukachine and Loeb, 2003, 2004)*

CERES BBR-like data

The CERES data to construct the training data sets have to reproduce the BBR observations:

- Three instantaneous radiances pointing the same scene at nadir (VZA 0 deg), forward (VZA +50 deg) and backward (VZA -50 deg) views

8 days of CERES along-track data employed

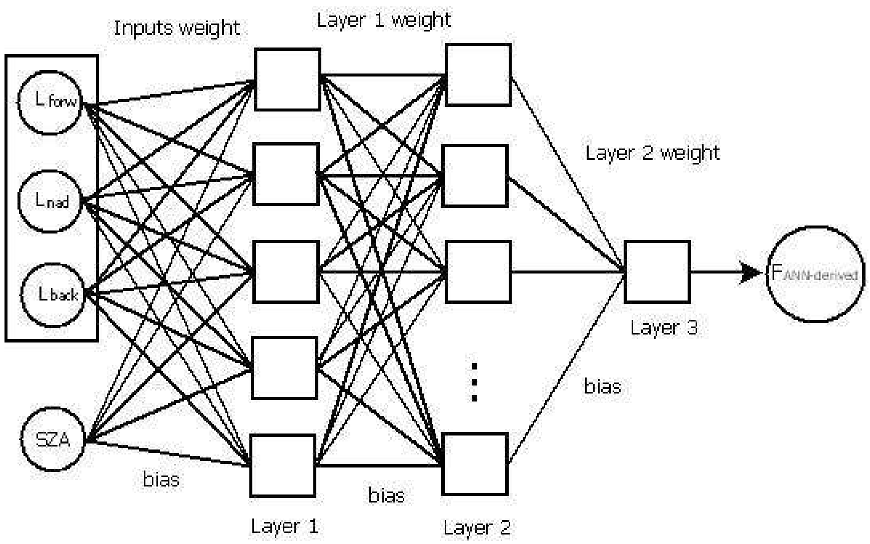
(2M of useful footprint triplets)

- 2 days of not-corrected along-track scanning
- 6 days true along-track scanning (Earth rotation correction applied)

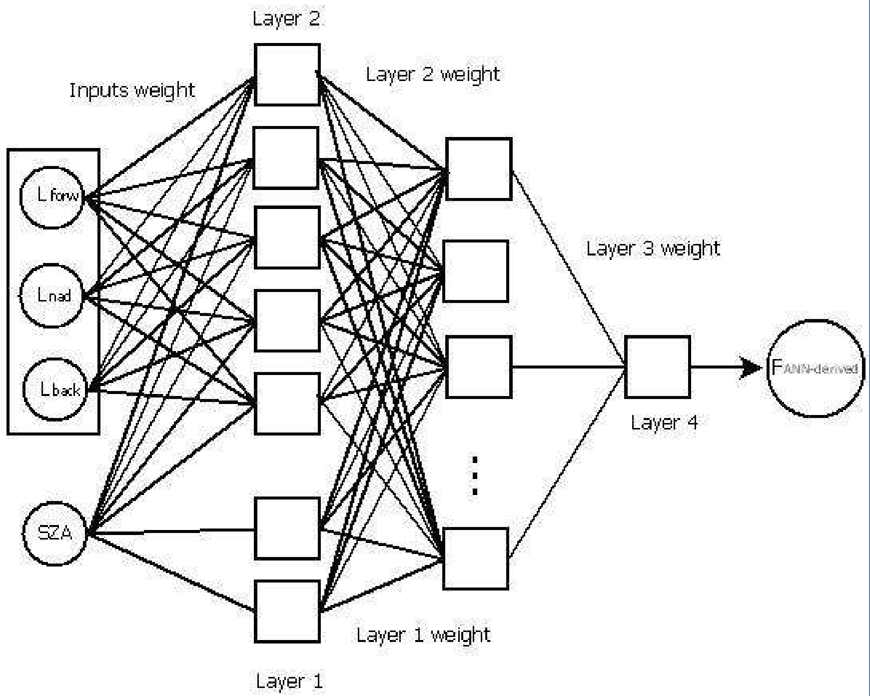
Along-track co-location between off-nadir views is only possible to achieve it in the CERES true along-track scan mode

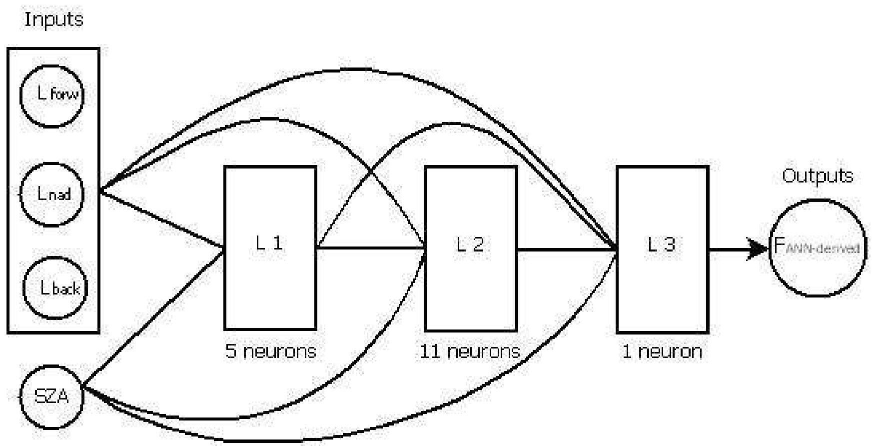
Back-propagation neural network structures

Feed-forward ANN structure



Custom-forward ANN structure





Cascade-forward ANN structure

ADM scene schemes

ADM scheme 1

Training sets composed by ocean, land and snow/ice surfaces. cloudy conditions are part of the statistic background data.

ADM scheme 2

Scene types defined as a function of the atmospheric conditions, clear-sky or cloudy sky. Assumed surface effect is less important than cloud anisotropy in the radiance-to-flux conversion

ADM scheme 3

Set of 9 types that corresponds to the CERES ID definitions. Clouds as well as surface properties are considered in this scene definition.

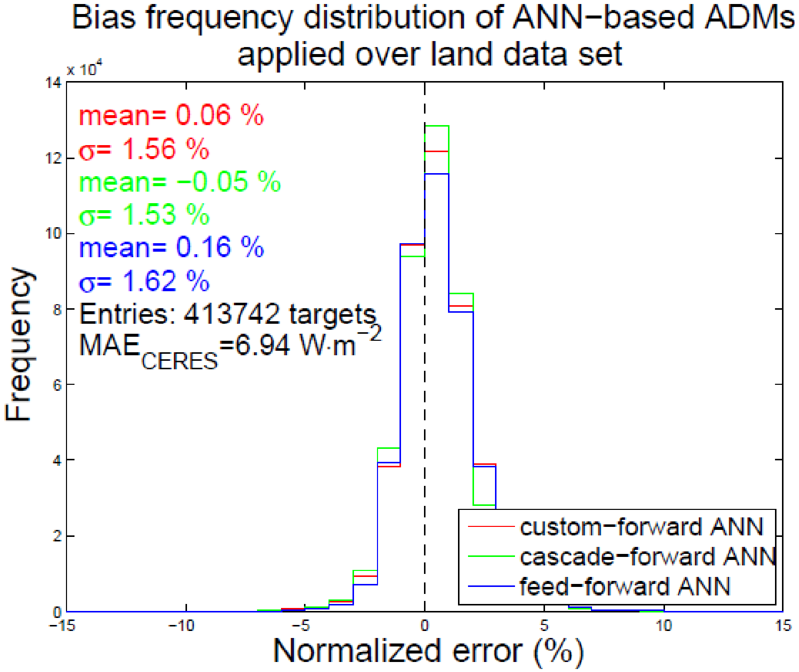
BBR ANN-based flux estimates

Procedure:

- Create the input vectors
- Normalize input and output variables to the factors used to create the training sets
- Normalized input data are propagated through the trained ANN
- Normalization of the output is reversed and flux estimates are obtained

To evaluate the three architectures the ANN performance is tested for the entire BBR-like data base

Example: ANN-based ADMs corresponding to land scene type of scheme 1 applied over original the CERES SSF files



ANN architecture selection

A single ANN is chosen for every ADM scheme and for each scene type

12 error metrics computed: STD_{min}, RMS, NRMS, STD(MAE), bias, MAE, NMB, NME, MFB, MFE, NME and NMB. The neural network with the maximum number of minimum error values is selected

ANN	STD_{min} (Wm^{-2})	RMS (Wm^{-2})	BIAS (Wm^{-2})	MFB (%)	MAE (Wm^{-2})	MFE (%)	MAE_{CERES} (Wm^{-2})
custom-forward	5.310	3.427	0.746	0.649	2.523	1.444	4.947
cascade-forward	5.308	3.402	0.668	0.616	2.523	1.443	4.947
feed-forward	5.334	3.629	0.967	0.851	2.710	1.655	4.947

Entry vectors in the CLEAR training set: 873

Number of CERES footprints evaluated: 522449

custom-forward	6.680	5.308	0.309	0.211	4.048	1.826	6.672
cascade-forward	6.691	5.347	0.097	-0.061	4.076	1.848	6.672
feed-forward	6.703	5.340	0.082	0.027	4.071	1.833	6.672

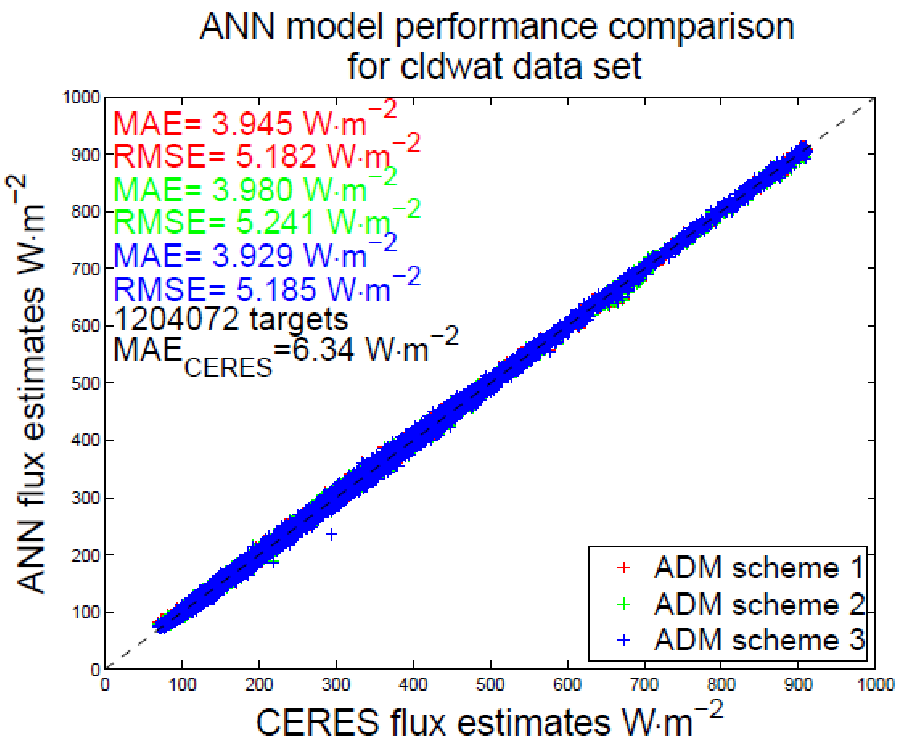
Entry vectors in the CLOUDS training set: 2899

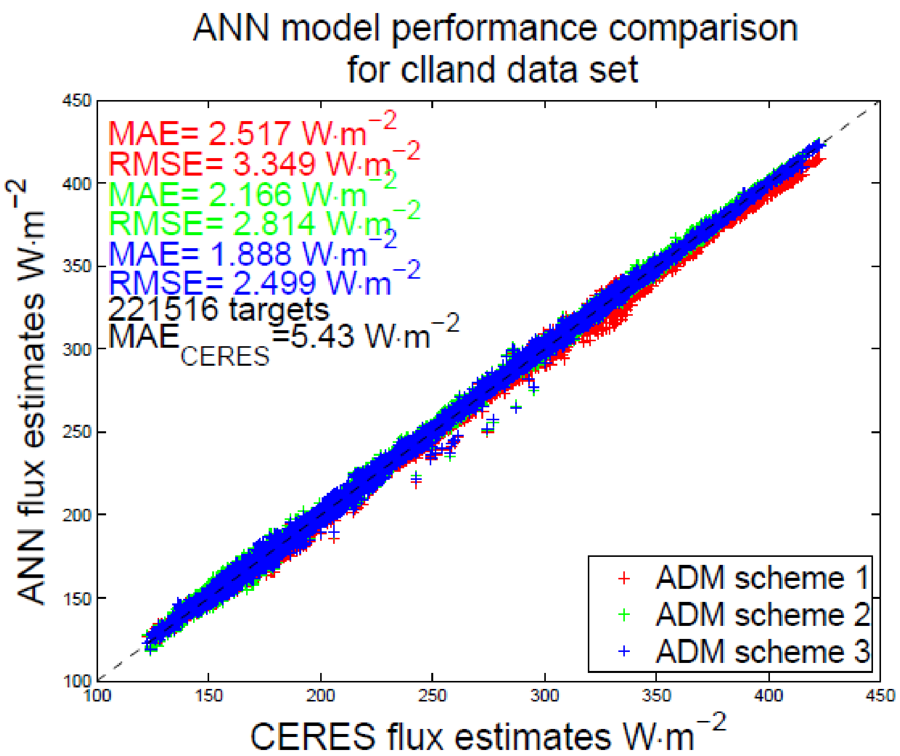
Number of CERES footprints evaluated: 1407672

This example summarizes some error metrics achieved for the ANN-based ADM with the scene scheme 2

ADM scheme selection

ADM scheme 3 provides the **most accurate** results. However, averaged errors obtained in the ADM schemes 1 and 2 could be acceptable as well.





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Longwave BBR flux estimation: work plan

Scope: Retrieve instantaneous longwave radiative fluxes from the multi-directional broad-band and multi-spectral radiance measurements performed on-board the EarthCARE satellite

Goal: Develop radiance-to-flux conversion algorithms using synthetic ADMs

Methodology: Study based on a data base construction of spectral radiance fields at TOA using radiative transfer calculations. Following the operational procedure used for LW GERB flux estimation methodology *(Clerbaux et al., 2002)* and previous BBR studies *(Domenech, 2008)*

Assumptions:

- The combination of the off-nadir and nadir views into an artificial effective radiance improves the flux inversion accuracy

- The correlation between the broad-band radiances and the spectral behaviour of the radiation field can be exploited to reduce the thermal flux retrieval error

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Spectral radiance data base

Radiative transfer code

Longwave radiative transfer calculations performed with the **libRadtran** software package v1.4 *(Mayer and Kylling, 2005)*

Molecular absorption parameterized with the **LOWTRAN band model** *(Pierluissi and Peng, 1985),* as adopted from the SBDART code *(Ricchiazzi et al., 1998)*

DISORT2 radiative transfer equation solver *(Stamnes et al., 2000)*

- discrete ordinate (16 streams, clear-sky; 48 streams, cloud cover)
- atmosphere plane-parallel
- 5 cm^{-1} spectral resolution (4 – 50 μm)

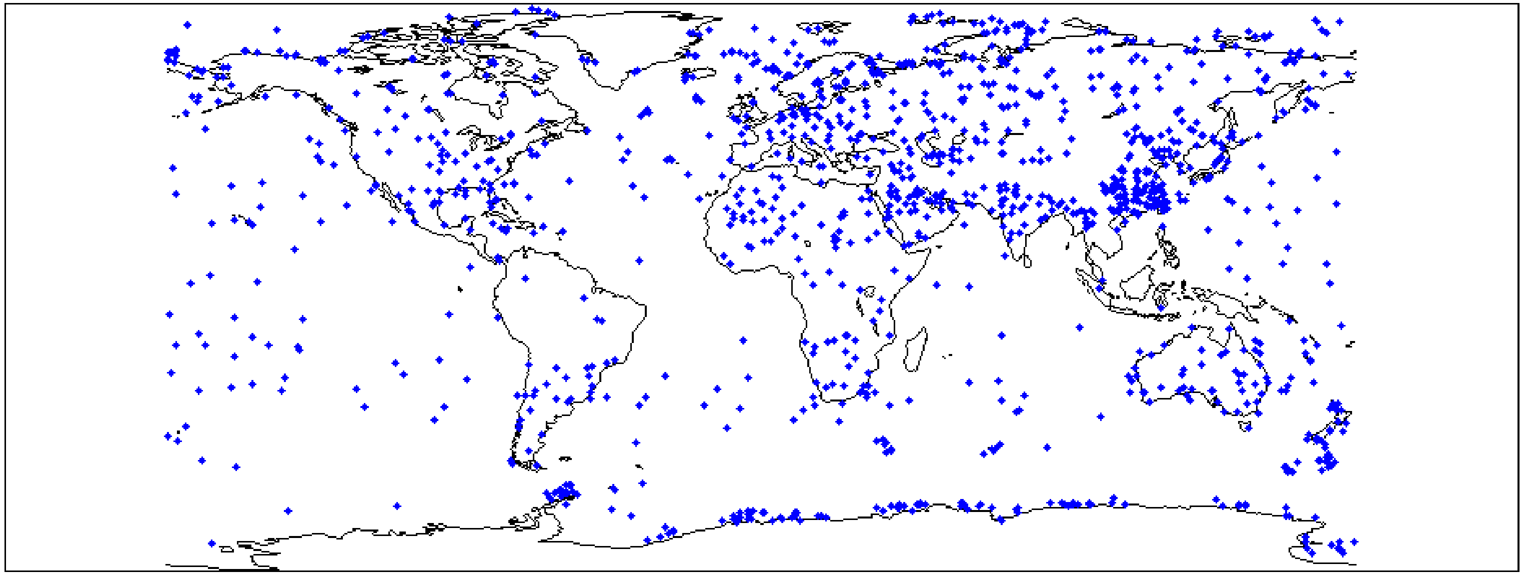
Atmospheric profiles adapted from **TIGR2000_v1.1** data base *(Chedin et al., 1985; Chevallier et al., 1998)*

Ice optical cloud properties similar to Key et al., 2002. **Water properties** using pre-calculated Mie tables

Atmosphere profile

TIGR2000_v1.1 data base contains **2311** atmospheric profiles of **temperature**, **water vapor mass mixing ratio**, **ozone mass mixing ratio** at **40 pressure levels.** These have been extended according to the corresponding standard atmospheres *(Anderson et al., 1986)* by:

TIGR database profile locations



Cloud conditions

The cloud cover has the highest influence in the anisotropy of the radiance field → Important to use realistic statistics for the input cloud parameters

Climatological analysis based on **CALIPSO** data

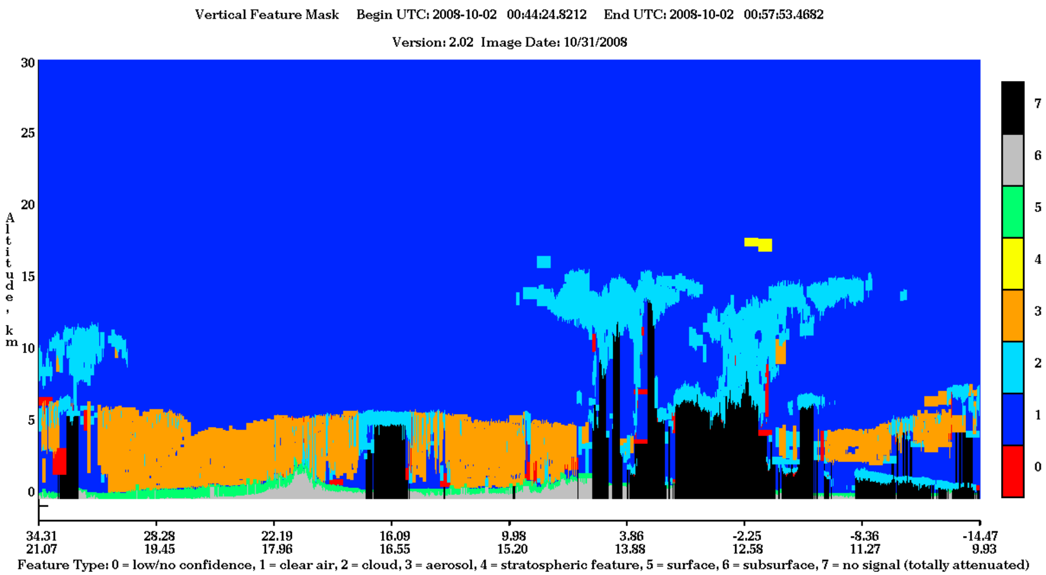
Products employed:

Lidar Level 2 Vertical Feature Mask v2.01

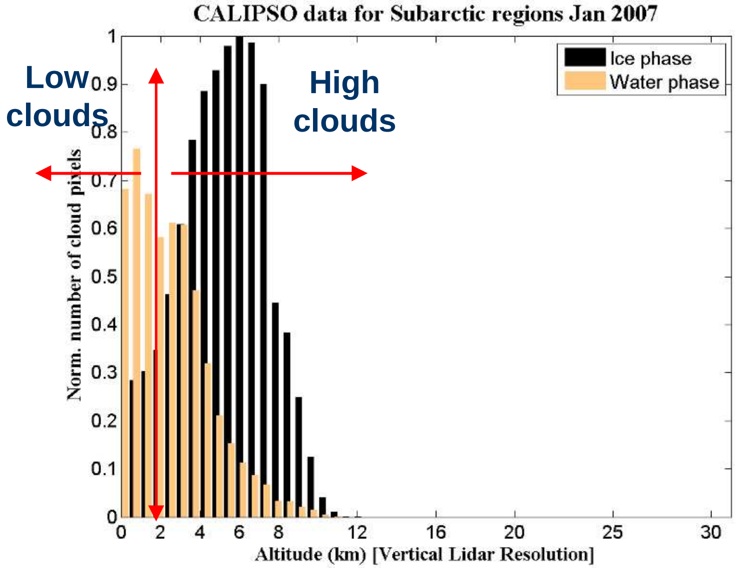
1 month of data (01/2007)

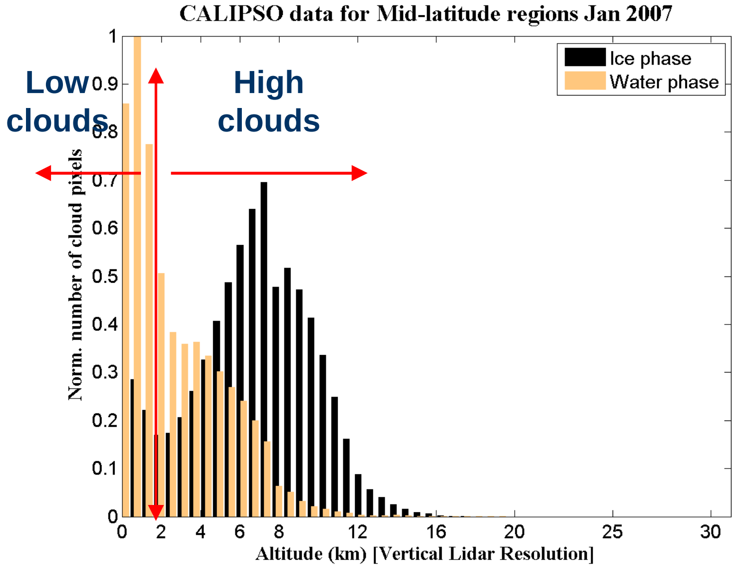
50 orbits processed

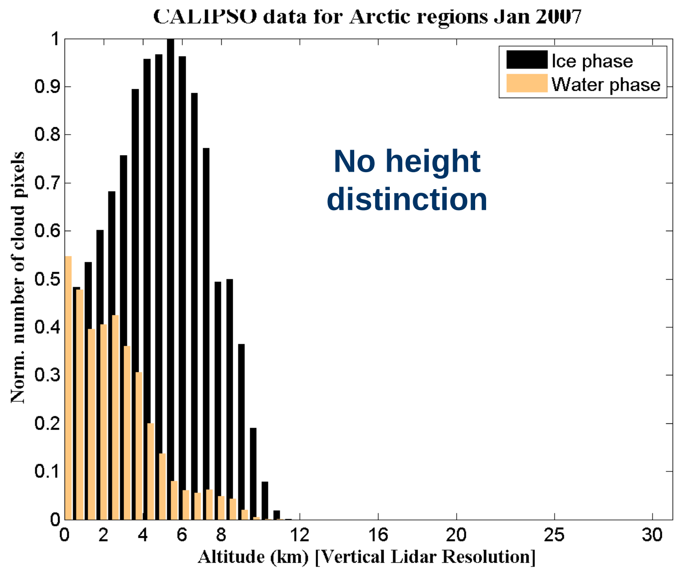
Employing 10% of pixels

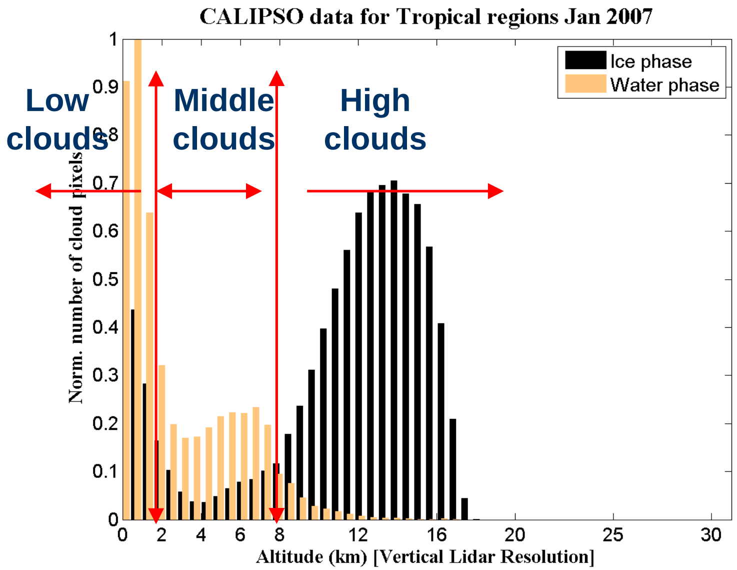


CALIPSO analysis: first results



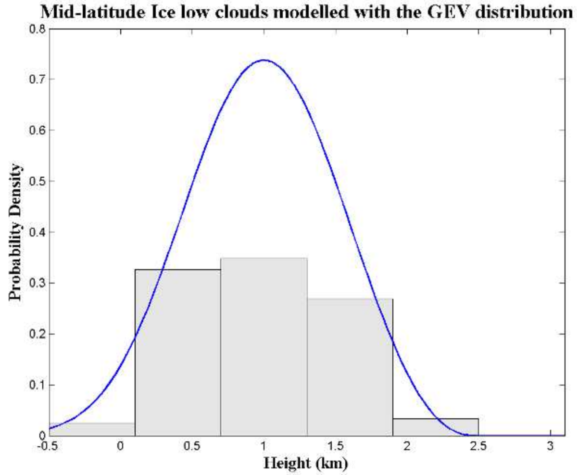


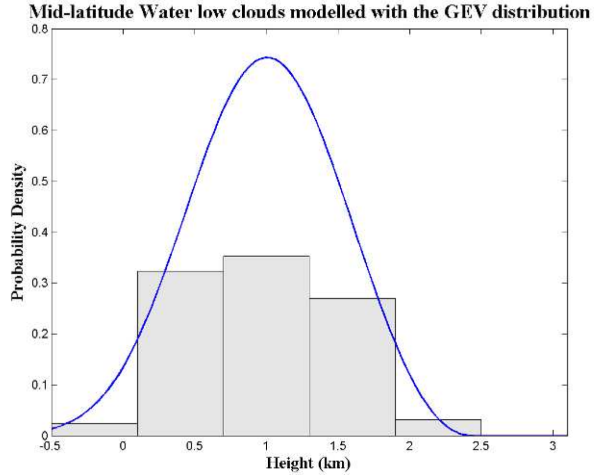




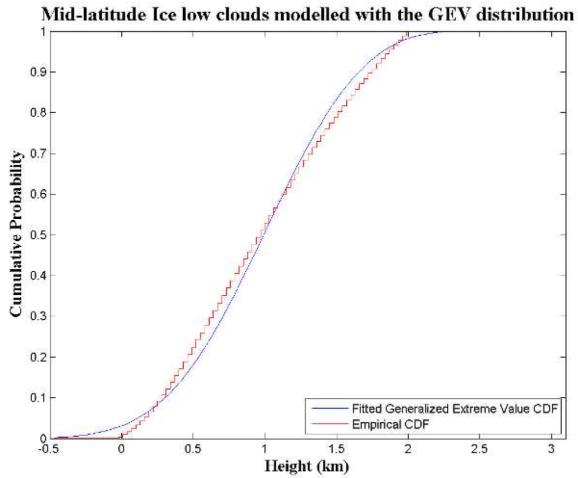
Clouds statistics

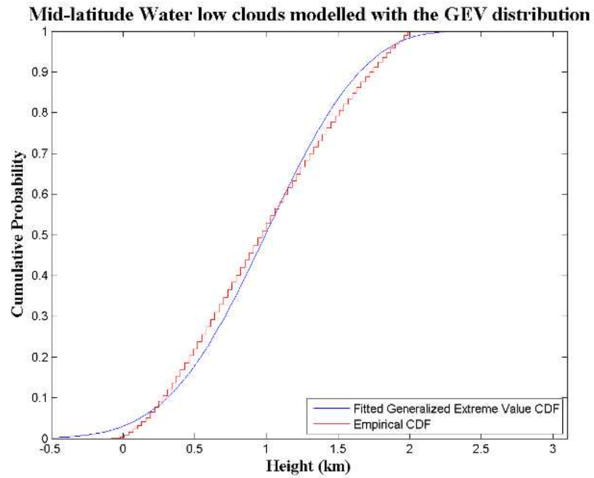
Statistics are obtained by fitting the CALIPSO processed data to the **GEV** (Generalized Extreme Value) distribution function





cloud phase, thickness and altitude coupled for the different latitudinal bands



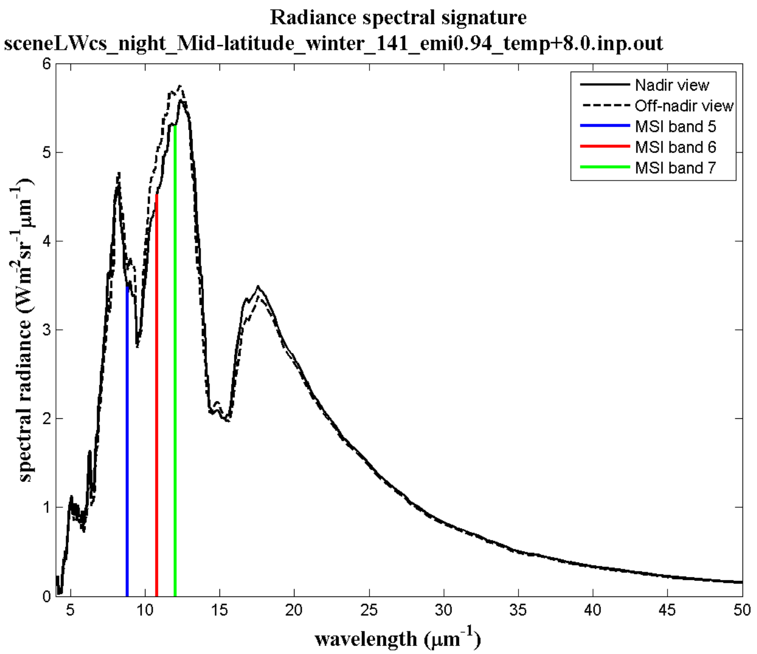


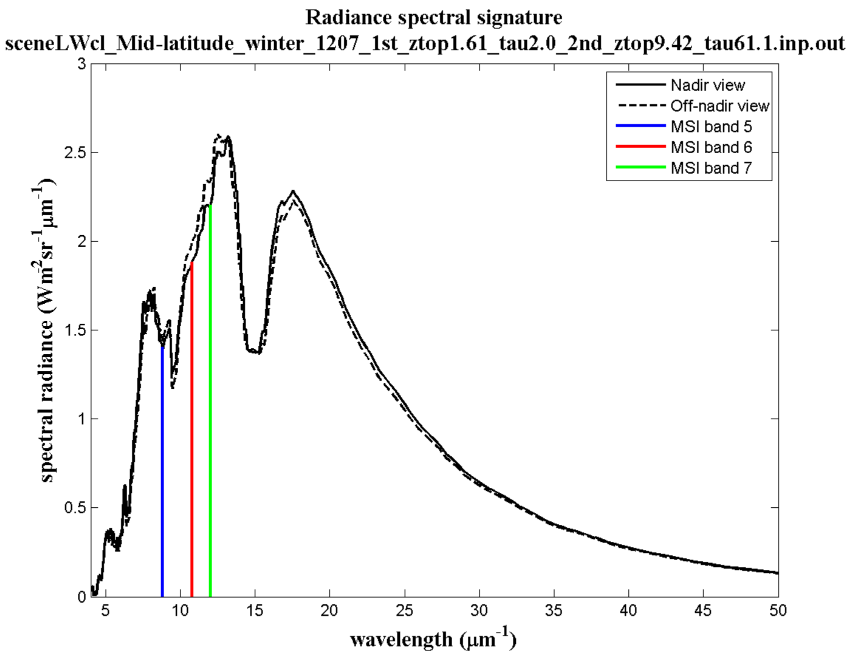
Output example:

Ice and water clouds for mid-latitude atmospheres

Data base construction

- 9 789 radiance fields computed for the thermal region of the solar spectrum
- At the BBR viewing angles (nadir and off-nadir view at 50 deg). *It is assumed that thermal radiance is independent on the relative azimuth angle*
- One half of the data base is used to fit the models on the data
- The second half is employed to evaluate the developed angular models



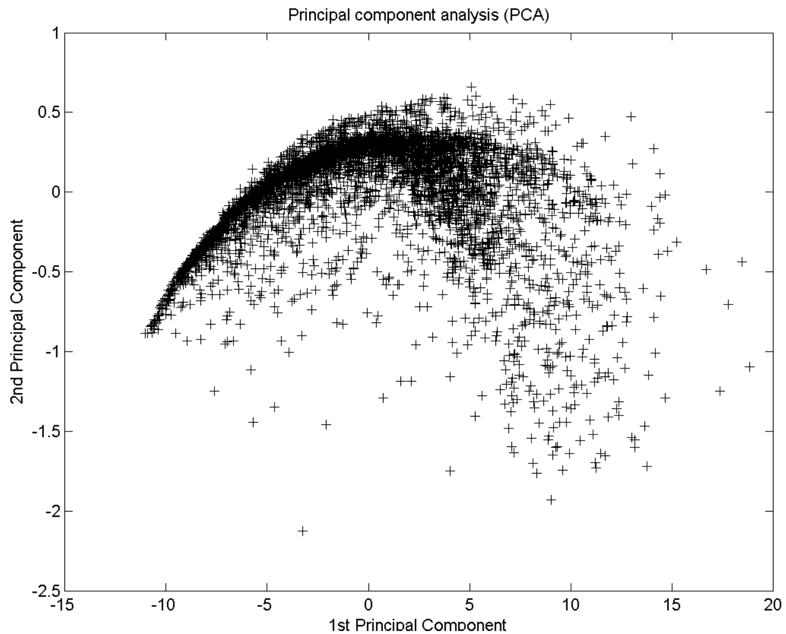


Spectral models

Using spectral information from multiple MSI measurements

A direct use of the three MSI measurements in high order regressions produces lot of coefficients (35 coeffs for 2nd order, 70 coeffs for 3rd order, etc)

Principal Component Analysis (PCA)

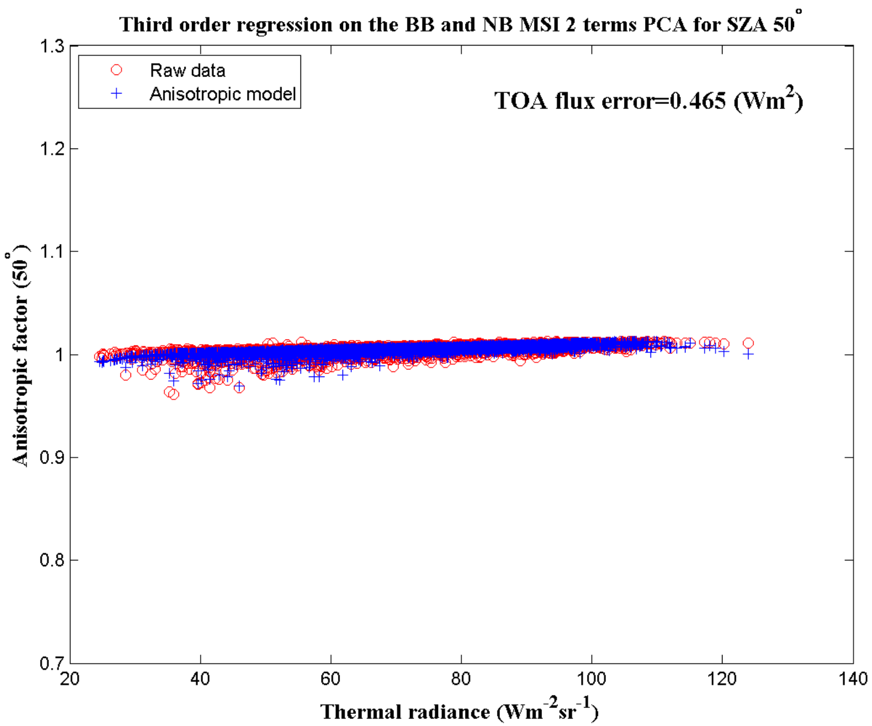


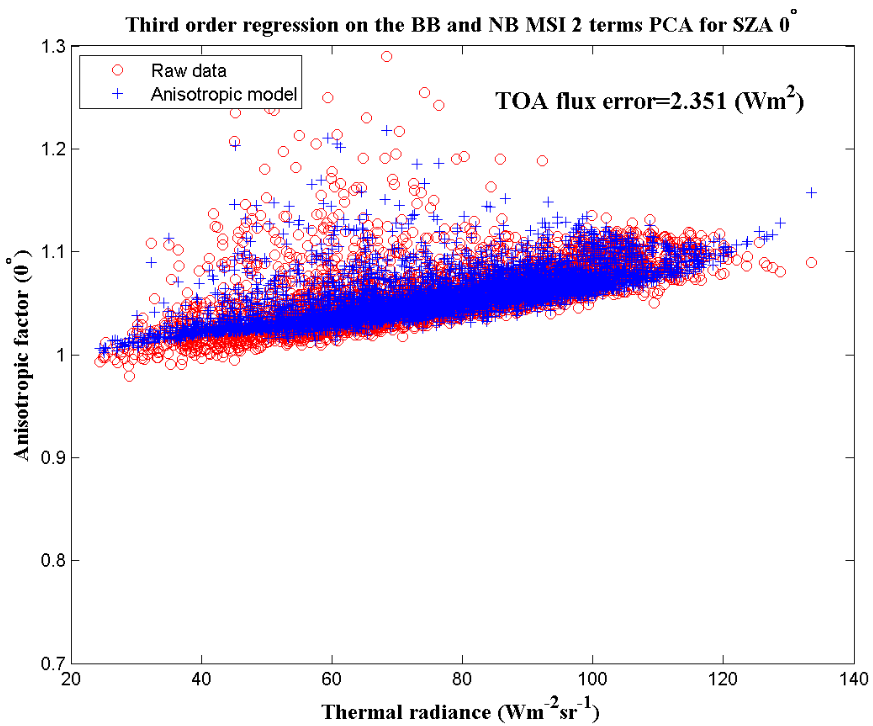
Spectral information is projected on the principal component axis (linear transformation) and the angular models are constructed on a restricted set of the principal components

Multi-spectral models

Using 1st and 2nd terms of MSI Principal Component Analysis

$$R(\theta, L, L_{PCA1}, L_{PCA2}) = a_0(\theta) + a_1(\theta)L_{PCA1} + a_2(\theta)L_{PCA2} + a_3(\theta)L(\theta) + a_4(\theta){L_{PCA1}}^2 + a_5(\theta){L_{PCA2}}^2 + a_6(\theta)L^2(\theta) +$$
$$+ a_7(\theta)L(\theta)L_{PCA1} + a_8(\theta)L_{PCA2}L(\theta) + a_9(\theta)L_{PCA1}L_{PCA2} + a_{10}(\theta){L_{PCA1}}^3 + a_{11}(\theta){L_{PCA2}}^3 + a_{12}(\theta)L^3(\theta) + a_{13}(\theta)L_{PCA1}L_{PCA2}L(\theta) +$$
$$+ a_{14}(\theta){L_{PCA1}}^2 L_{PCA2} + a_{15}(\theta)L_{PCA1}{L_{PCA2}}^2 + a_{16}(\theta){L_{PCA1}}^2 L(\theta) + a_{17}(\theta)L_{PCA1}L^2(\theta) + a_{18}(\theta){L_{PCA2}}^2 L(\theta) + a_{19}(\theta)L_{PCA2}L^2(\theta)$$





Multi-angular model

BBR allows measuring three along-track radiances coming from the same source at almost the same time

When ADM classical definition is extended to use this extra angular information the radiance-to-flux conversion is improved *(Bodas et al., 2003; Domenech, 2008)*

Effective radiance methodology

$$R = \frac{\pi I}{F}$$ where I is the effective radiance,

$$\breve{L}(\theta, scene) = \sum_{n=0}^{2} c_n(scene)\,\theta^n = c_0 + c_1\theta + c_2\theta^2$$

$$I(scene) = \int_{-\pi/2}^{\pi/2} \breve{L}(\theta, scene)\,|\sin\theta|\cos\theta\, d\theta$$

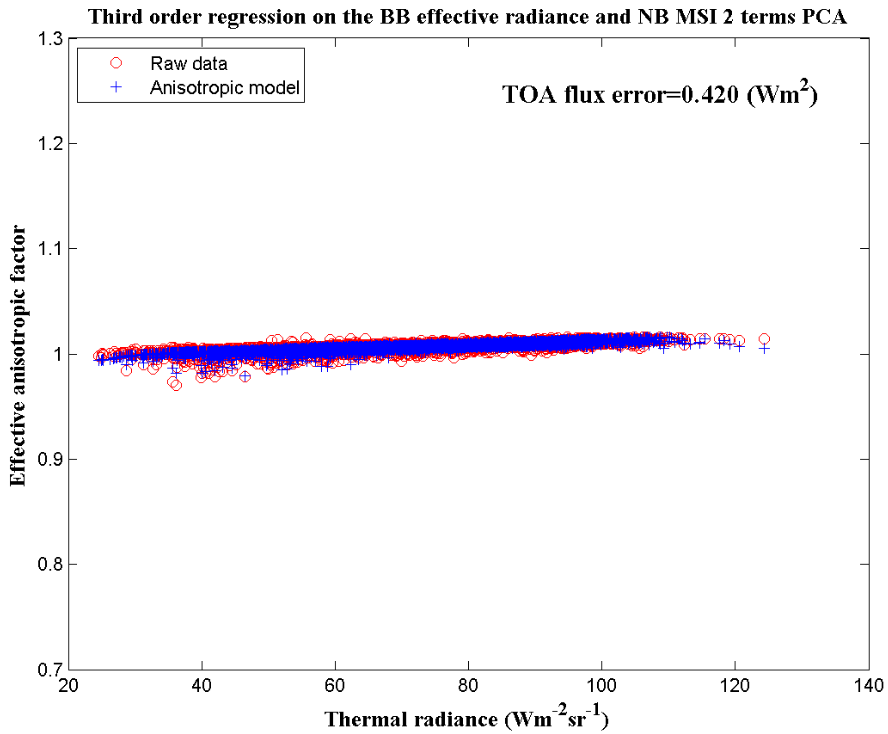
where $\breve{L}$ is the second degree polynomial fit of the three along-track average radiances as function of the viewing zenith angle

The effective radiance is defined as an integral limb to limb along the viewing zenith angle

Multi-angular and multi-spectral model

Third order regression using the BBR BB effective radiance and two terms of the Principal Component Analysis of MSI data

$$R(I, L_{PCA1}, L_{PCA2}) = a_0 + a_1 L_{PCA1} + a_2 L_{PCA2} + a_3 I + a_4 L_{PCA1}^2 + a_5 L_{PCA2}^2 + a_6 I^2 +$$
$$+ a_7 I L_{PCA1} + a_8 L_{PCA2} I + a_9 L_{PCA1} L_{PCA2} + a_{10} L_{PCA1}^3 + a_{11} L_{PCA2}^3 + a_{12} I^3 + a_{13} L_{PCA1} L_{PCA2} I +$$
$$+ a_{14} L_{PCA1}^2 L_{PCA2} + a_{15} L_{PCA1} L_{PCA2}^2 + a_{16} L_{PCA1}^2 I + a_{17} L_{PCA1} I^2 + a_{18} L_{PCA2}^2 I + a_{19} L_{PCA2} I^2$$



Allows a reduction of the radiance-to-flux conversion error up to:

- **82%** with respect to nadir multi-spectral model
- **10%** with respect to off-nadir multi-spectral model
- **18%** with respect to multi-angular model

Conclusions

- The efficiency of SW BBR ANN-derived fluxes to reproduce SW TOA CERES Terra fluxes has been successfully tested

- BBR stand-alone fluxes are derived with an acceptable accuracy without MSI information. BBR imager-dependent fluxes could be obtained with higher accuracy when MSI data is available

- It is shown the improvement of the thermal radiance-to-flux conversion using BBR multi-directional broad-band and MSI multi-spectral radiance measurements

- Scene ID based ADM methods, such as SAB method, lead to consider additional errors (mis-identification of L2 MSI retrievals). This approach solves this issue

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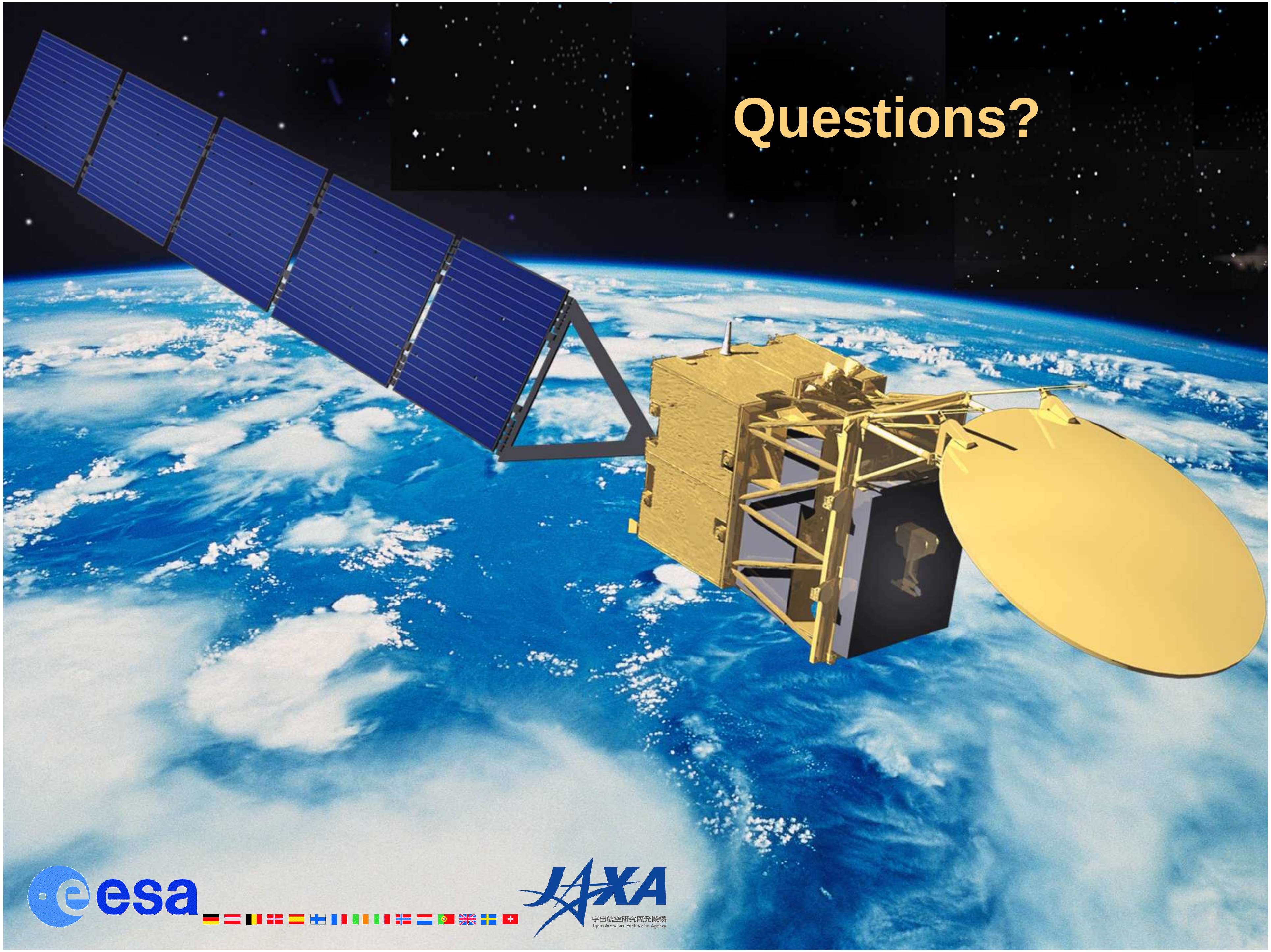

Questions?

Backup Slides

EarthCARE science objectives:

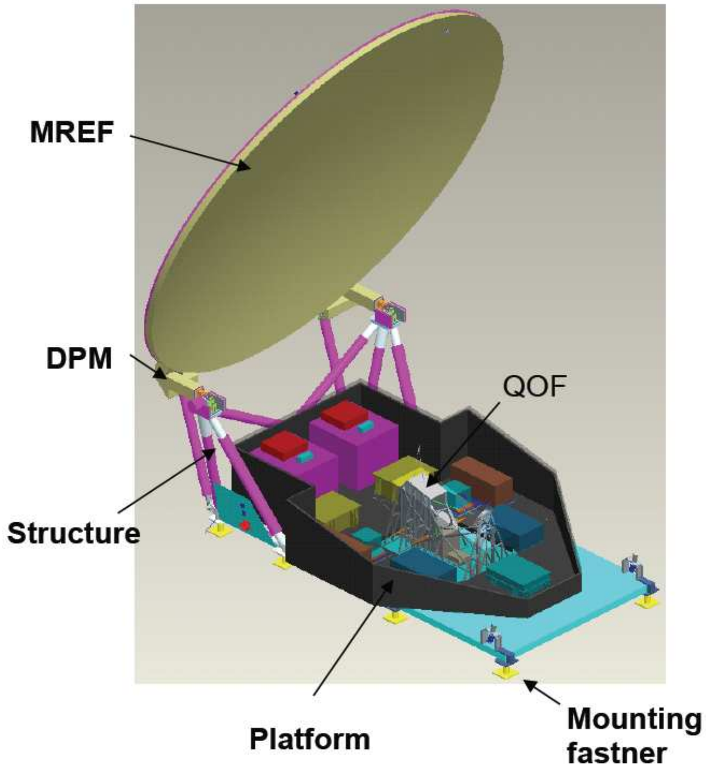
Quantify **cloud-aerosol-radiation interactions** so they may be included correctly in climate and numerical weather prediction models to provide:

- **Vertical distribution** of atmospheric **liquid water and ice** on a global scale, their transport by clouds and radiative impact
- **Cloud overlap** in the vertical, **cloud-precipitation interactions** and the characteristics of vertical motion within clouds
- **Vertical profiles** of natural and anthropogenic **aerosols** on a global scale, their radiative properties and interaction with clouds
- The **profiles** of atmospheric **radiative heating and cooling** through a combination of retrieved aerosol and cloud properties

Active Instruments: The Cloud Profiling Radar (CPR)

- High power W band (94 GHz) radar
- Doppler capability
- Horizontal resolution: approx 750 m
- Altitude range: surface to max 20 km
- Vertical resolution: 500 m with sampling every 100 m
- Horizontal sampling: 500 m
- *Level 1 product: Reflectivity and Doppler profiles*

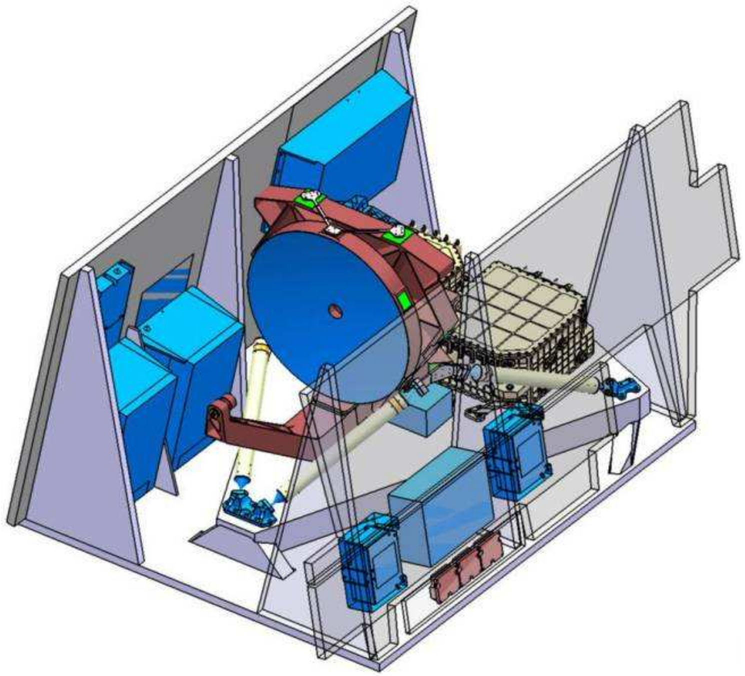
Contribution of **JAXA**



CPR Instrument Concept

Active Instruments: The Atmospheric Lidar (ATLID)

- Backscatter UV (355nm) Lidar
- High-Spectral Resolution optical receiver (HSRL)
- 3 channels:
    - Rayleigh scattering channel
    - Co-polar scattering Mie channel
    - Cross-polar scattering Mie channel
- Altitude range: surface to 30km
- Vertical resolution:
    - < 100m up to 20km
    - 500 for 20-30km
- Horizontal sampling: 100m
- *Level 1 product: attenuated backscatter profiles*

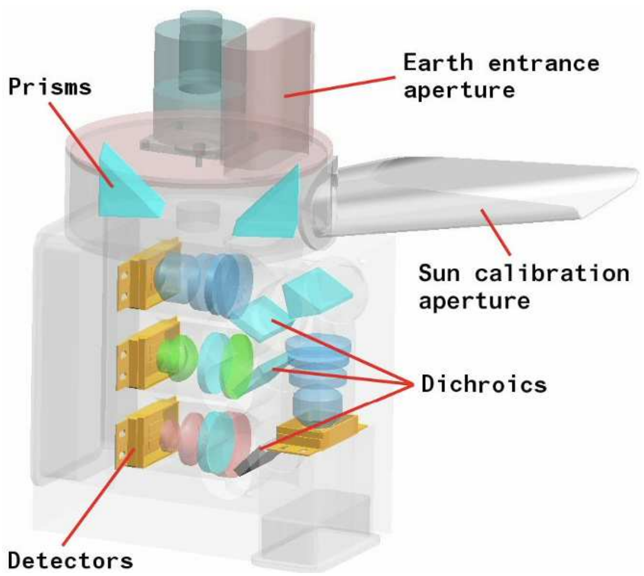


ATLID overview

Built by Astrium-SAS with GA as sub-contractor

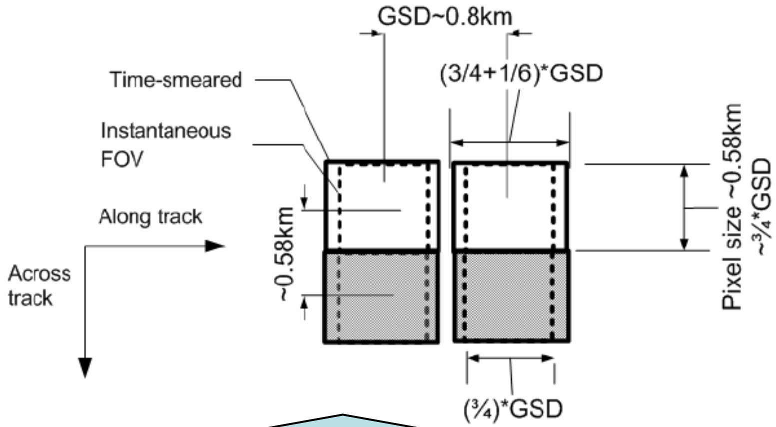
Passive Instruments: Multi-spectral imager (MSI)

- Across-flight track information / scene
- 7 Channels (4 SW + 3 LW):
  - Vis (670nm)
  - NIR (865nm),
  - SWIR (1.67, 2.21µm)
  - TIR (8.8, 10.8, 12.0µm)
- Swath 150km (de-pointed because sun-glint)
- Pixel size: 500m
- Push-broom operating mode
- *Level 1 product: Top-of atmosphere radiances and brightness temperatures in 7 spectral bands*



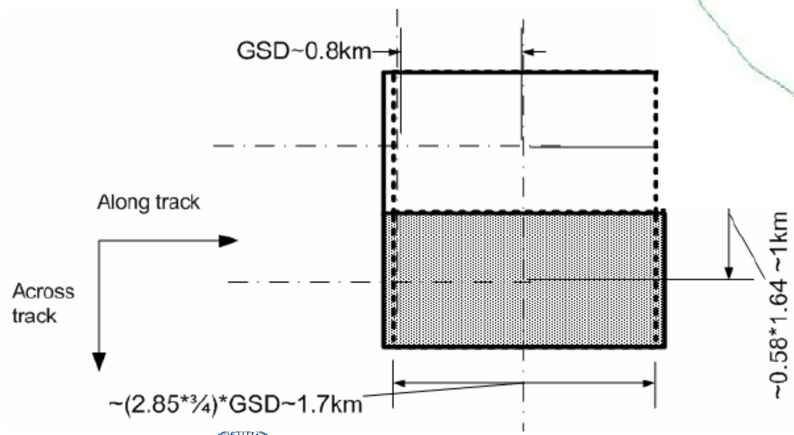
MSI Instrument Concept

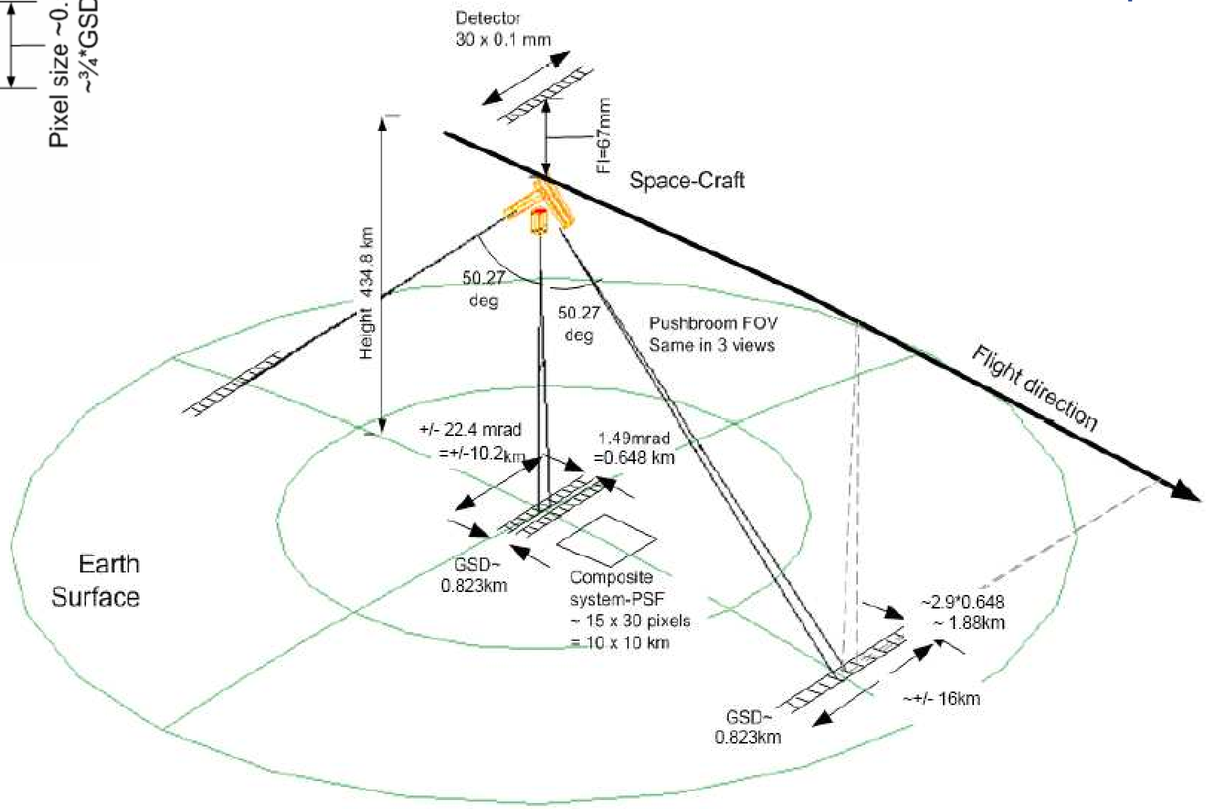
Built by SSTL with TNO as sub-contractor



Nadir px footprint, min. orbit 377 km, dashed line @ 50% PSF contour, exposure smear is 1/6 GSD

Oblique px footprint, other conditions as for nadir footprint



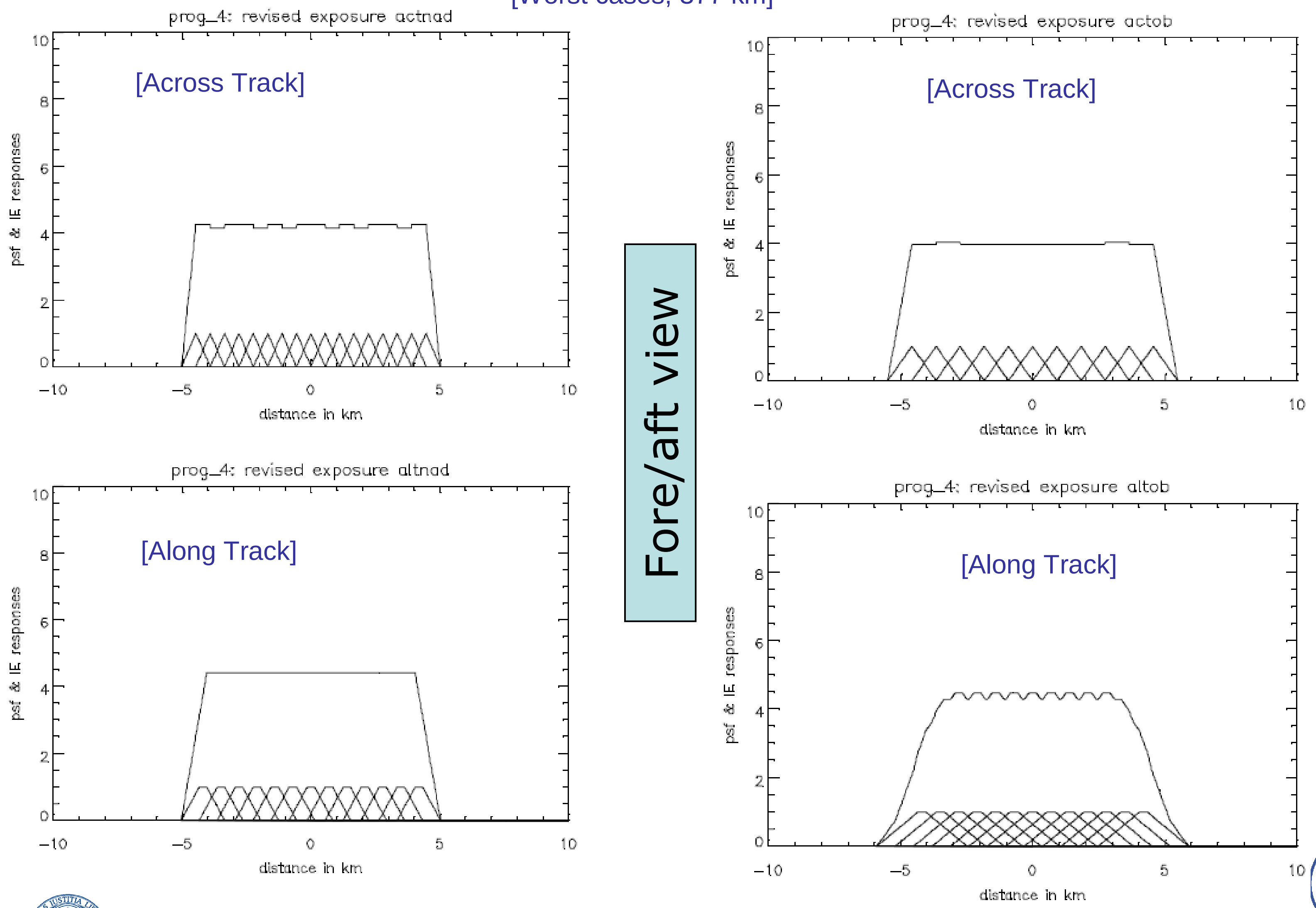


BBR Instrument Concept - PSF

[Worst cases, 377 km]

Nadir view

Fore/aft view



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GEOPHYSICAL (LEVEL 2) PRODUCTS

SINGLE-INSTRUMENT PRODUCTS (LEVEL 2a)

ATLID

Feature mask

Target classification

Extinction, backscatter, depolarisation

Aerosol extinction, backscatter, type

Ice water content (empirical)

MSI

Cloud flag / cloud type

Cloud phase

Cloud top temperature / height

Effective cloud particle radius

Aerosol optical thickness

CPR

Feature mask

Target classification

Ice water content / eff. Radius

Liquid water content / eff. Radius

Vertical motion

Precipitation / snow

BBR

LW unfiltered radiances

GEOPHYSICAL (LEVEL 2) PRODUCTS

SYNERGISTIC PRODUCTS (LEVEL 2b)

ATLID+MSI

Cloud top height

Aerosol optical thickness

Aerosol type

BBR+MSI

SW unfiltered radiances

TOA SW & LW flux estimates

ATLID+CPR+MSI

Target classification

Ice water content / eff. Radius

Liquid water content / eff. Radius

Aerosol extinction / type

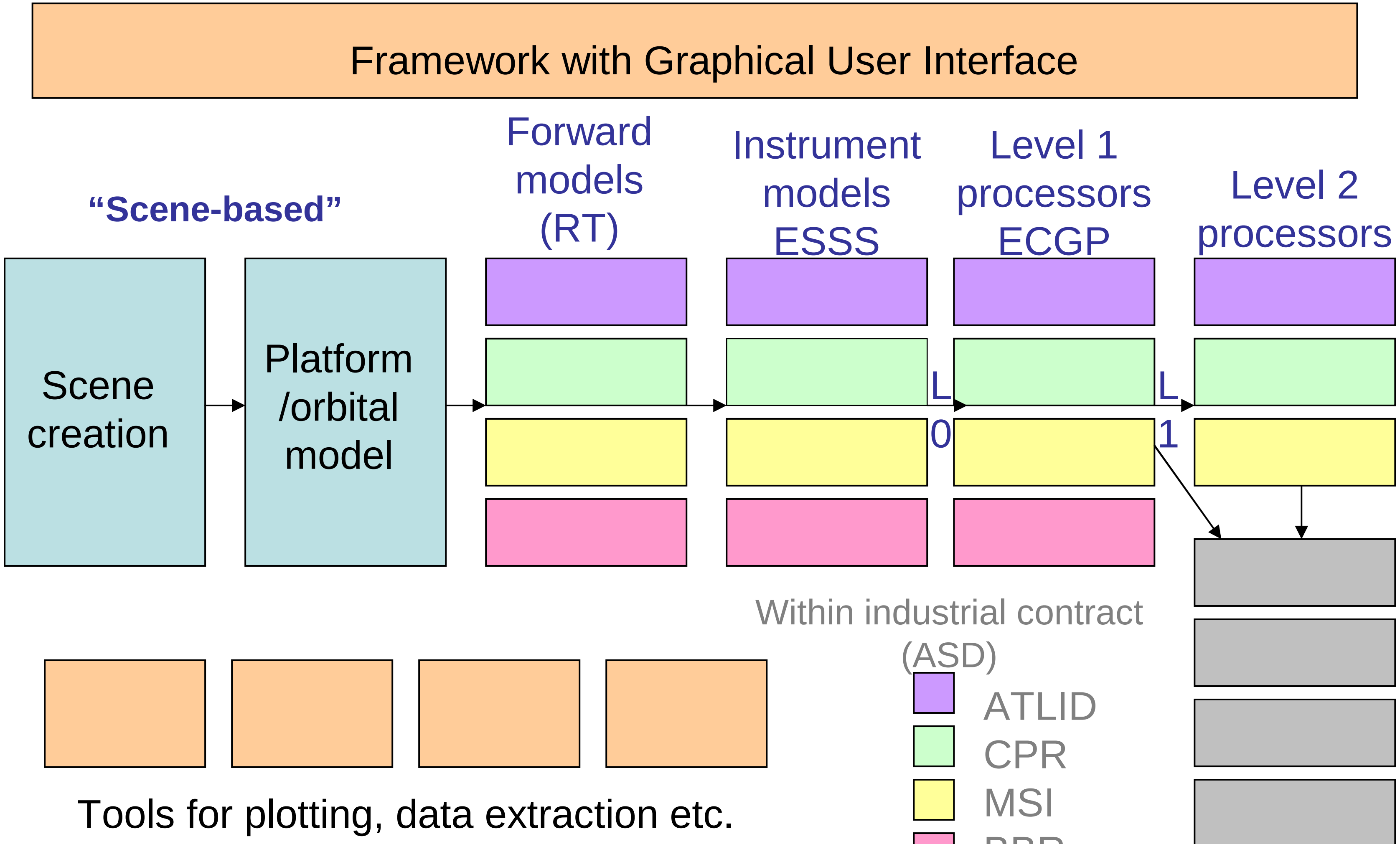
Rain water content / rain rates

Cloud fraction and overlap

Reconstructed TOA radiances

Flux and heating rate profiles (calculated from above cloud & aerosol parameters)

ECSIM: END-TO-END EarthCARE SIMULATOR



Built by KNMI and Deimos

Freie Universität Berlin

BBR science goals

Objective: To derive instantaneous TOA fluxes with 10 Wm^{-2} accuracy (including instrument and unfiltering errors). However…

$$F(\theta_0) = \int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} L(\theta_0, \theta, \phi) \cos\theta \sin\theta d\theta$$

Measured by satellite

- Radiances measured at single angle. Fluxes cannot be instantaneously obtained (insufficient angular sampling)
- Angular Distribution Models (ADM) correct the anisotropy deviation from the lambertian case

$$F(\theta_0) = \frac{\pi L(\theta_0, \theta, \phi)}{R(\theta_0, \theta, \phi)}$$

Lambertian flux

Anisotropic factor

take the mean behavior of the anisotropy of the radiance field into account, in order to allow the flux retrieval from a single radiance measurement

LEVEL 2 ACTIVITIES

Overall phasing

2009/10	Scientific algorithm development ⇨ ATBD v1
2011	Processor implementation ⇨ ATBD v2
2012	ATBD peer review, processor consolidation

Ongoing ESA activities

QuARL	Assimilation into ECMWF models
ICAROHS	Multi-wavelength HSRL aerosol retrievals
DAME	Doppler radar
SITS	Broad-band radiometer unfiltering
IRF ESTEC	Angular models to retrieve TOA radiative fluxes
RATEC	Radiative transfer models
IRMA	MSI clouds and aerosols incl. ATLID synergy
ATLAS	ATLID retrievals + synergistic target class.

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